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REAL-TIME CONDITION BASED MAINTENANCE FOR HIGH VALUE SYSTEMS

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Abstract: Many industries operate high value equipment – often remotely -- that requires reliable performance in severe environments. Similarly, the U.S. Navy's submarine Towed Array Systems (TASs) stress conventional approaches to operating and maintaining this system level capability comprised of integrated hydraulic, mechanical, electronic and acoustic sub-systems.

The Navy invested in a Condition Based Maintenance (CBM) proof of concept for an individual ship TAS by developing the Thinline Health Monitoring System (THMS). THMS collects real-time discrete reliability data and synchronizes this data with other historical information and the TAS's current condition assessment. As a predictive "intelligent code" it uses Bayesian Belief Networks (BBNs) to extract the full value of real-time data and provide a complete range of system performance evaluations -- from diagnosis to prediction.

Drawing upon THMS' success, the U.S. Navy supported expanding this capability fleet-wide to encompass health assessments of the entire submarine TASs population. Plans have been developed to build a relational database that is accessible to a geographically separated towed systems community via the Internet for interactive analysis and diagnostics.

These system level analyses and first principal processes are directly translatable to other government and commercial critical systems that cannot afford unscheduled -- or unnecessary -- maintenance.

Key Words: Condition based maintenance; Maintenance; Prognostics; Reliability

INTRODUCTION: Submarine Towed Array Systems (TAS) stress conventional approaches to operating and maintaining a system level capability necessary for ships' operations. TASs are mission essential for obtaining acoustic information in support of a high percentage of critical submarine deployments. By itself, a TAS is a complex configuration that requires integrated remote operation of hydraulic, mechanical,

electrical, electronic and acoustic subsystems in a severe ocean environment. It is nearly impossible to observe the full functioning of each TAS component during operation. Further if malfunctions occur at sea, most failures require repairs to be deferred until return to port. Repairs are frequently costly, and when performed waterborne, have the potential to result in negative work through repair activity induced failures associated with poor accessibility and an adverse repair environment. Adopting a prognostic Condition Based Maintenance (CBM) capability completely alters the TASs' maintenance landscape by monitoring current system conditions and predicting failures so that necessary repairs can be completed in advance under favorable conditions.

At the individual ship system level, the U.S. Navy invested in a proof-of-concept Thinline Health Monitoring System (THMS) for an OA-9070/TB-23 thinline towed array baseline configured SSN 688 Class submarine [1]. THMS provides a real-time method for assessing the current condition of the TAS and demonstrates the ability to dynamically predict future system health. The principal elements that support this capability are real-time sensor inputs, a mature Reliability Centered Maintenance program, and an embedded Bayesian Belief Network (BBN) "intelligent" code. Having demonstrated a prognostic, next generation maintenance capability for individual systems, the U.S. Navy funded CBM concept development for the fleet population of towed arrays. Integral to this capability is a comprehensive discrete historical and real-time web-based relational database and a powerful software toolbox to permit diagnostic and prognostic information mining simultaneously to geographically separated users (including operators, design engineers, vendors and logisticians). The inherent object oriented BBN tree framework permits the extension of the THMS health assessment output to serve as an input to the overarching BBN population model. A similar approach is directly applicable to other systems and industries.

BACKGROUND: The Navy's core maintenance efforts reside in a Reliability Centered Maintenance (RCM) program. RCM uses statistical information derived from historical data in order to develop maintenance practices for satisfactory system performance. The shortfalls associated with a stand-alone RCM program have been well-articulated [2][3]. Up front, its usefulness is dependent upon the quality of the database supporting the program. Many factors influence the nature of the database including the quality of data inputs, available validated test data and system level cause-and-effect data, and scalability [4]. Second, considerable system level understanding is required to select a suitable mathematical performance model. The modeler must inevitably make assumptions to characterize failure behavior. Frequently these assumptions are over-simplified and at best are based upon statistical formulations. Finally, there are often real-life events that introduce inaccuracies in the selected model. What effects do improved replacement components have on system reliability? Is it true that following maintenance, the component is returned to "as new" condition? Is it reasonable to assume that no degradation in system or component performance occurs when component inspections are performed as part of preventive maintenance? Can the model accommodate unrealized conditions characteristic of real systems such as localized hot bearings, peak starting currents, clogged lubrication ports, prolonged operational periods

in extreme environments or downstream effects when failures to non-critical components occur?

When RCM is applied to a complex system, it often practically leads to an exhaustive and costly maintenance program that requires a number of compromises affecting system operations and base-line program execution. Some of these compromises are (1) frequent system shutdowns to conduct maintenance inspections, (2) premature component replacement to hedge against system failures, and (3) high logistics costs – and hence total ownership costs -- to maintain a spare components stockpile. Submarine TASs typify the compromises and excessive costs that have become associated with maintaining a complex, high value system.

For submarine TAS, a voluminous database has been constructed from a number of sources to attempt to track and statistically gain performance insight. Beyond the shear exhaustive effort required to collect this data, because of the universe of reporting sources, data has frequently been incomplete or has been inadequately characterized to identify failure modes. The net result has been an amalgamation of data that has not provided the necessary insight to deliver the best possible RCM program, much less lead to a next generation CBM capability. Only through the goal to deliver a TAS CBM program has an initiative to make sense of years worth of TASs data taken shape and meaningful distribution models for selected critical components been developed.

Submarine TAS also labor under the real-world realities that can frustrate achieving desired system reliability. While component and subsystem design processes account for reliability (frequently through an expression of operational availability Ao), when these reliability factors are aggregated to reflect a composite system reliability design factor (if they can) the desired multi-system reliability either falls short of the goal or is strained over system life. For complex systems such as towed arrays, reliability must be addressed up-front through a separately considered maintenance program. TAS maintenance has attempted to improve reliability at great operational and fiscal cost through a variety of hedges that include frequent intrusive inspections and wholesale replacement of major components (such as the entire $1 million array itself) prior to submarine deployments.

THINLINE HEALTH MONITORING SYSTEM (THMS): THMS was built to provide a data collection, storage, condition health assessment and dynamic prognostic capability for a single submarine's TAS, which is comprised of four principal sub-systems; mechanical, hydraulic, electrical and acoustic signal path. Up front, the power of THMS resides in its ability to collect 39 reliability relevant signals real-time, analyze, and then integrate the incoming data stream with other logged discrete reliability data (including previous maintenance and repair or replacement actions). Synchronizing this incoming data stream with historical data results in a current condition assessment. The assessment is at once updated and passed to THMS system memory, and when combined with THMS' Bayesian Belief Network (BBN) "intelligent code," provides an empirical foundation to reliably predict future TAS performance at three operator selected future periods. The end result is an effective risk management system that avoids

"unexplained" reliability failures, provides updated analyses, and uses feedback to improve TAS performance over time [1].

Hardware: THMS hardware is a rugged stand-alone PC package (7.25" x 17.5" x 16") that provides the interface between the analog shipboard Thinline TAS equipment sensors and its embedded software. It is comprised of the following components:

- PXI Chassis with Back-plan Bus (National Instruments based)
- Embedded Computer with 4 GB Hard Drive
- 32 Channel 1.25 MB Analog-to-Digital (A/D) Converter
- Terminal Blocks
- Interconnecting Cables
- Electronic Components for Signal Conditioning and Attenuation
- Flat Screen Monitor
- Keyboard and Mouse

THMS taps the input signals through a high impedance multifunction Input-Output (I/O) card. The architecture of these cards include:

- NI-PGIA gain independent, fast-setting-time instrumentation amplifier
- DAQ-STC counter/timer
- RTSI multi-board/multi-function synchronization bus
- MITE PCI bus transfer interface, and
- Shielded, latching metal connectors [5]

The various input signals are paralleled into the THMS system through a breakout connection and terminal block. These signals are fed into the THMS to perform both single and multiple A/D conversions of a large number of samples. The THMS can perform multiple A/D conversions operations with programmed I/O, interrupts, or Direct Memory Access. The THMS interface software provides for operator interface and governs all aspects of interaction between the hardware and embedded BBN software.

Software: THMS uses a tailored version of two off-the-shelf software products, LabVIEW and Microsoft Visual C++. The software interface module collects and stores real-time input data at a rate of 4 Hertz from selected OA-9070/TB-23 sensors through the THMS Breakout Box. Additionally, the interface module facilitates the display of real-time data, provides data to the BBN decision tree for analysis, and receives analyzed and resulting metric data from the BBN for display. THMS provides multiple user screen variations for input and output displays, and at the functionally highest levels, data trending and system health

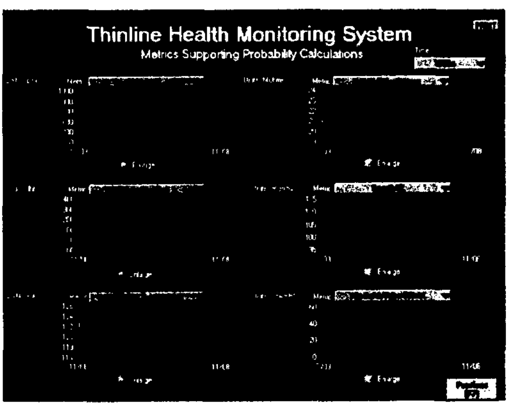

Figure 1. THMS Metrics Display Screen

assessments. Figure 1 illustrates the THMS Metrics Display Screen that is used to show reliability relevant metrics and provides a trend indication of key operational parameters critical to subsystem performance. Figure 2 illustrates the THMS Total and Sub-Group Health User Screen that provides the probability that the TAS will operate successfully. The probabilities are calculated for the total system and the four major system sub-groups using the embedded BBN software code [5].

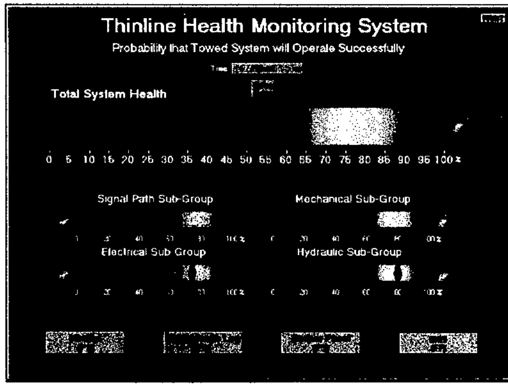

Figure 2. THMS Total and Sub-Group Health User Screen

Bayesian Belief Networks (BBN): At the core of THMS is a BBN structure. It serves as the analytical vehicle to interpret the TAS physical model through reliability analysis and directly provides failure likelihood estimates. Although there were other methods that could have been used – including neural net algorithm training -- BBNs were particularly well suited for TASs because they are tailored to a system-level physical model and are naturally object-oriented. Training an algorithm alone without regard to the physical cause for failures was limited by insufficient data. The data did not include all failure contingencies nor did it represent the actual operating environment. Further, algorithm training did not include a physical understanding that related to predictions and therefore, provided little diagnostic benefit. On the other hand, all that was required to construct the THMS BBN was a connection between an input measurement value and the likelihood that a hypothesis related to that measurement was true. A THMS BBN could be tested and constructed in a qualitative manner independent of data with data being needed to refine the model, not to define it. Finally, if new failure modes became known after model construction, they could easily be added without starting over again.

In general, each BBN component -- represented by a node -- receives input in the form of other measurements or likelihood ratios and produces output linked to other nodes in the form of likelihood ratios. The BBN structure, including the links constructed between nodes, provides a knowledge fusion that relates to the causes of each failure mode (or component) to their consequences (measurement). The BBN fuses system component performance specifications and normal operating parameters or failure probability distributions to form a relationship between each measurement and the likelihood for each possible hypothesis regarding healthy system operation [6]. Although BBNs are typically designed to convert measurements into likelihoods, these "measurements" can take on almost any form from a data concentrator to the system response function of component failure, or even alternative Artificial Intelligent sources. BBNs can even

calculate the posterior probability of a node failure given the evidence of all other nodes. In this way the probabilities are revised as our uncertainty and knowledge changes [7].

As applied to THMS, the top-level BBN nodes for a TAS are provided in Figure 3. The figure shows the connection between the probability of operation of each TAS subsystem and the probability of operation of the TAS as a whole. Each ellipse represents a node in the decision tree. Each sub-system (node) is further modeled and coded in its own complex decision tree. Having been constructed from the physical model and an understanding of the TAS, the embedded BBN or "intelligent code" takes the conditions of a single TAS as provided by the sub-system level sensors and turns them into predictions of successful operation.

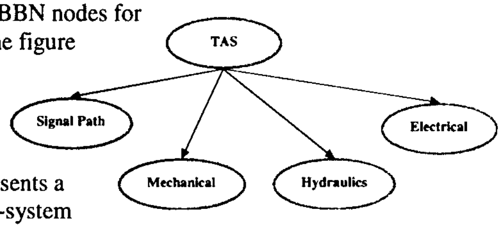

Figure 3. THMS Towed Array System BBN

PROGNOSTIC CAPABILITY FOR FLEET TASs POPULATIONS: Because the BBN schema identifies the probability for a component or sub-system as part of the conditional probability for the entire system, it followed that the THMS BBN tree could be extended to the program level. Figure 4 illustrates this top-level BBN structure. Although yet to be analyzed to this top program level, the U.S. Navy has studied the logical extension of the THMS BBN to the second order Fleet-wide tier [8].

Developing a Fleet-wide prognostic CBM TAS capability made sense from a number of

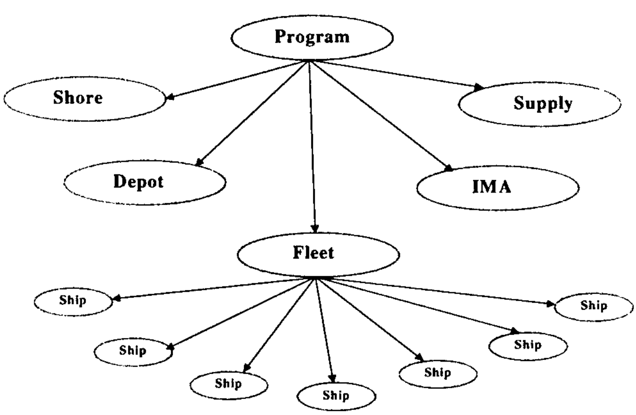

Figure 4. Top-Level TAS BBN Structure

perspectives. By assessing the health of many TASs simultaneously, a feedback process could be established for individual TASs to define a more accurate normal operating condition. This feedback is essential to ensure that individual systems are compared equally to a single standard, and that the standard is fully representative of composite operating system behavior. Second, a comprehensive discrete and real time database could be built that is updated real-time by established data format, validation, and consistency procedures. This database will support the highest quality answers to traditional RCM maintenance failure questions, real-time diagnostic evaluations, and will establish a baseline TAS prognostic CBM capability. Third, as a result of this meaningful, population-wide database, a powerful software toolbox can be fully utilized. Tools can be provided that go far beyond the straightforward cataloguing of Out of Commission (OOC) counts, failures by type and description, and graphing trends over time. Finally, making the database Internet accessible and using web-based formats allows: comparison checks between past performance and current trends using defined metrics, statistical analysis of data referred by specific categories through web browsers, and longitudinal trends and cross-correlation examinations. These are just some of the more meaningful capabilities that will be possible to a geographically separated towed systems community.

Database: Data is entered from a number of sources to an automated centralized database connected to the Internet. Entries can occur either manually through the THMS data logger feature or by Personal Digital Assistants (PDAs) carried by field personnel, or automatically through the automatic THMS function. The data is warehoused on a regular schedule by using Data Transformation Services (DTS) and is saved as a package that includes tasks executed in a coordinated sequence of steps. The DTS units also set aside data entries that have errors or inconsistencies with previously collected data in an Exception Log that is available to the Database Administrator for data reconciliation. Based upon the type of data errors and inconsistencies observed, a subsequent rule-based set of DTS units can subsequently be constructed to accept certain data characteristics as valid.

After the build has been created and saved, it is completely self-contained and can be retrieved by using the database server's Enterprise manager or a DTS utility. In this fashion, the data warehouse provides users with rapid analysis of large data volumes – including investigations of hypotheses for comparisons across and between data groups -- through a variety of network management protocols including indexing, data base de-normalization, star or snowflake schema, and aggregations.

Finally, as the database grows over time, overall performance may be affected by a degraded system response time. Assuming 570 MB of data per month is accumulated per submarine, the database will grow at 340 GB per year with a fleet of 50 submarines. In order to retain a historical database for long-term analysis while maintaining system performance, the database can be archived annually on discs that are retained indefinitely and later disposed when no longer needed [9].

Toolbox: Because of past processing limitations, simplistic analytical assumptions were often made in order to address more complex reliability issues. In the end the resultant analytical conclusions were contradicted by experience. Today's processors permit more powerful survival analysis techniques similar to those pioneered for medical research. These techniques permit statistical inference and data extrapolation within error bounds which in turn, provides reasonable tools to predict the degree of difference between similar articles, the peril rate of articles following from identified failure modes, and the effects of time on future failure events. To cite one example, a recent reliability study on towed array modules showed that the previous simple exponential failure distribution fell far short of accounting for the effects of module aging. Through proportional hazards modeling and competing risk formulations, a two parameter Weibull distribution for module life has since been highly correlated with historical data. While a marked improvement, this was done acknowledging that the time basis for analysis was from available data. With the construct of a rigorous database, it will be possible to provide further time-based granularity for specific times of operation, handling, power-on and other periods of interest. This example points to the feasibility and need for a TASs Toolbox that provides a family of statistical techniques to (1) validate a specific mathematical model in order to describe failure and repair times, and (2) describe specific systems and deliver comparisons between groups within a population [8].

In the first case, the Toolbox can be equipped to investigate situational questions such as how to understand the interaction between external hydraulic oil and TAS performance. This can be accomplished by executing Analysis of Variance (ANOVA) routines that rely upon conducting comparisons or groupings. Other tools used to describe failure and repair times could include Hazard Functions, serial Correlation Tests, Trend Tests, and Post Maintenance or Inspection Differential Failure Rate Analysis.

In the second case, an application would be to expand the use of Fleet TAS operational availability (Ao). Currently, Ao is determined through steady state Markov chain probabilities for towed array and handler type only for attack submarines. With daily TAS data from all submarines, large-scale matrix multiplications for each category of Ao calculation will be required at the minimum once per month information interval. The Toolbox will not only be equipped to accommodate the additional data, but will be able to extend this Ao methodology to cover a variety of other meaningful subgroups of ships and systems including ballistic missile submarines, submarines readying for deployment and those actually deployed. Another useful comparison between groups would be a comprehensive survival analysis for array signal path components. The fidelity of component reliability distributions has already been improved through the comparison between the types of components within populations as newer components are manufactured and placed into service. Improved survival probabilities – beyond the 17 components of interest in the TAS signal path – will be possible through advanced competing risk and proportional hazards modeling that is based upon failure causes and sequential failure history. Significantly, this approach will allow the unique TAS configuration on any specific submarine to be analyzed for life predictions based upon individual components.

It's clear that by putting these tools in the Toolbox, significant diagnostic improvements are possible for TAS RCM. Most significantly, however, these tools will at the same time create the conditions for a BBN based Fleet-wide prognostic CBM capability. This results from the ability to include in the Toolbox the ability to formulate conditional probability density functions for all hypotheses being tested or by using inference. The former technique relies upon a fundamental understanding of the physical model while the later requires a statistical relationship between a measurement such as stress, and a key characteristic such as strength in order to provide the terms for the probability of failure given the measurement. These reliability connections appear in the BBN structure and fuse knowledge of the system with the expected behavior of each failure mode over time in order to predict the future time to the next fault.

Displays: Integral to the Toolbox's utility is its associated information displays. To achieve the highest possible value, displays will be provided using an Internet web page format with the capability to interface to the database from queries initiated from any user. Beginning with a Home Page, obvious trends will be highlighted in one section and the format will provide a convenient and consistent location for the metrics and details of daily importance. One-liner links to news stories with a somewhat larger description of events will be available that will provide follow-on links to the full story. Also included will be a search box that will allow Boolean operators to make specific searches. The Home Page will also include box scores and program indicators with recent changes, and links to categories of information depending upon the specific user's interest at the time.

Similar to financial web sites, beyond the Home Page will be an ever-expanded view of the data lying behind the information. By clicking on an area of interest in a data table or graph, a complete palette of selections will become available to display additional charts, tables, or graphs to permit analysis through comparison, correlation, or statistical review. Based upon user request, information and data can be displayed into numerous population sorts to include time dependent or independent displays, submarine class, geographic location, operational status, and array type and revision.

In the background, the Toolbox will continue to provide data analysis for formal routine reports. Not so obvious correlations, cross-correlations and partial correlations that exceed a specific coefficient threshold can be displayed as an optional page linked to the Home Page. Alert and focus pages tied to subject matter specific to a personalized user page can also be provided. For example an array engineer could add towed array and module subjects to his personalized page. Then, any time there are specific alerts to arrays or modules, the engineer would find an alert on his personal Home Page.

Finally, this web page structure significantly facilitates top-level TASs population management. End-of-year predications can accompany any Home Page linked item in order to provide managers useful indicators for what to expect from available data. Together with their accompanying error bounds, these predictions will put the data in perspective and will highlight the importance of taking action if the predicted outcome is undesirable [8].

CONCLUSIONS: The same characteristics of submarine TASs -- system complexity, significant impact to operations should failure occur, high repair costs, and adverse operating environments – are common to numerous other military and commercial projects. The costly inefficiencies of companion maintenance programs geared to attempt to achieve desired system reliability goals are also common.

There is a process that leads to the next generation maintenance solution for these complex systems. This process is defined by constructing a physical model that is based upon a system understanding and an analysis of existing reliability and maintenance data. As part of this development, additional data reduction or information is typically identified to create and validate the final model. Once the model is built, a solution can be engineered to meet reliability goals. Three tools in particular have proven useful to develop the solution; (1) a flexible architecture that permits predictive performance, (2) optimized processing power, and (3) web-based Internet accessibility.

Although other flexible architectures exist, BBNs have proven a particularly good fit for this system level approach. This is because of the BBNs' object-oriented structure, physical model based estimations, ability to fuse data with system knowledge, and tree structure. BBNs permit both externally and internally acquired system level knowledge to be included in prognosis. Finally, BBNs allow for a scalable capability that can be readily adjusted as system level understanding and growth both occurs.

Today's technology permits real-time processing of large data quantities and using sophisticated statistical models that go far beyond the simple assumptions that were common in the past. Because processors can be equipped with powerful analytical toolboxes, improved statistical reliability products and entirely new prognostic capabilities are possible.

Leveraging Internet technical and functional architectures provides the final piece for this next generation prognostic CBM. By creating relational databases founded upon Data Transformation Services, significant improvements can be made to ensure data validation and consistency and to conduct rapid analyses of data warehouses. Finally, simultaneous access to multiple geographically separated users qualitatively improves data analysis, focuses time critical diagnostic action, and creates shared efficiencies to program managers and site supervisors.

Following this approach used by the U.S. Navy for submarine towed arrays has the potential to significantly benefit any military or commercial sector that deals with costly time related failures that can be physically modeled. Particular cost-benefits may be possible for those high value systems that have significant maintenance costs and for which reliable system operation is important.

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